Main Injector Simulations for Project-X

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Overview

What is the Fermilab Main Injector
(and why do I simulate it)

Ingredients in the simulation

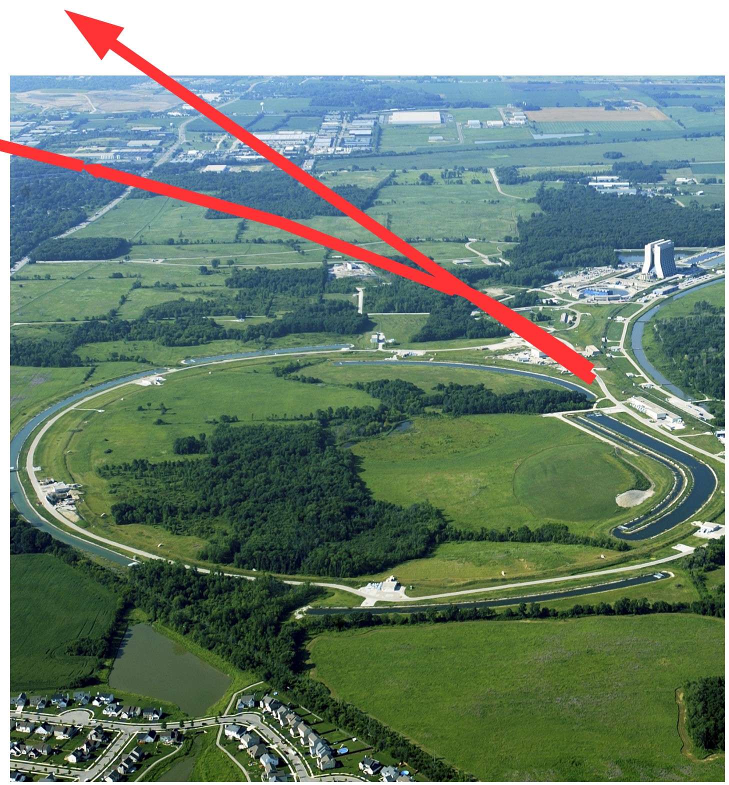
Results of the simulation

Discussion and future effort

The Fermilab Main Injector will be the workhorse of the Project-X high-energy, high-intensity physics program

MINOS and NOνA neutrinos to Soudan mine and Ash River (MN)

LBNE neutrinos to DUSEL (SD)



Main Injector in Project-X era

Current	Project-X
1.0×10^{11} protons/bunch	3.0×10^{11} protons/bunch
2.2 second/cycle	1.4 second/cycle
480 bunches	540 bunches
0.3 MW	2.0 MW

Space charge and impedance induced losses become worse at higher intensities, but must be kept to under 1%.

Use Synergia simulations to understand the origins and locations of losses.

Synergia components

Non-linear single particle propagation using CHEF libraries

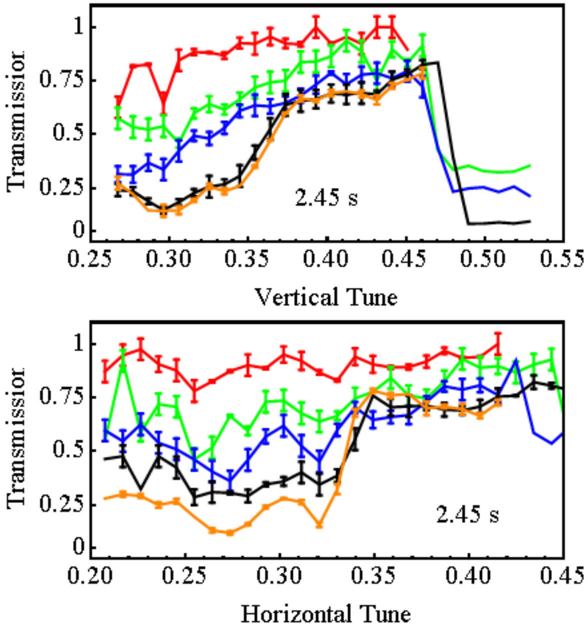
Simple and Complex Apertures

3D and 2.5D space charge solvers

For these runs, single particles trajectories are numerically integrated through fields. We use 3D (2.5D) space charge with open boundary conditions.

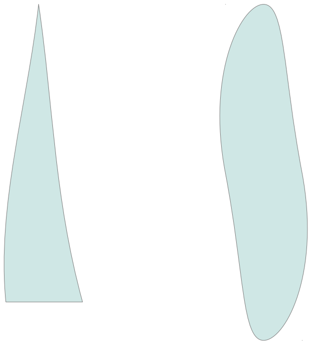
Compare simulation results to Main Injector studies (Spring 2012)

Transmission vs Tune

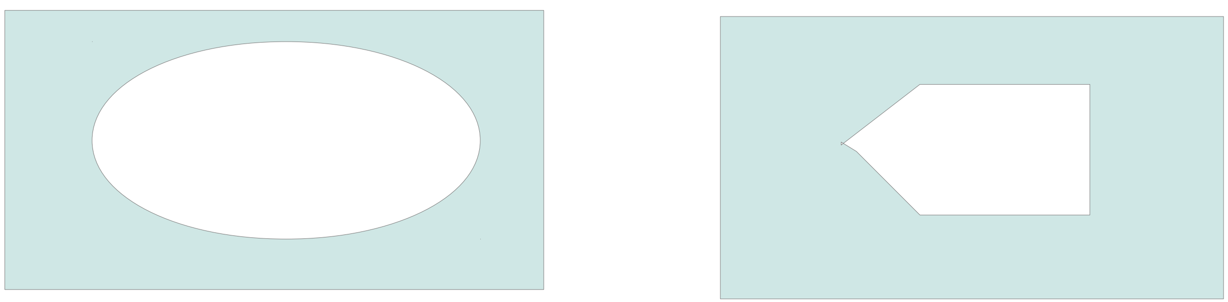


Usual suspects for losses

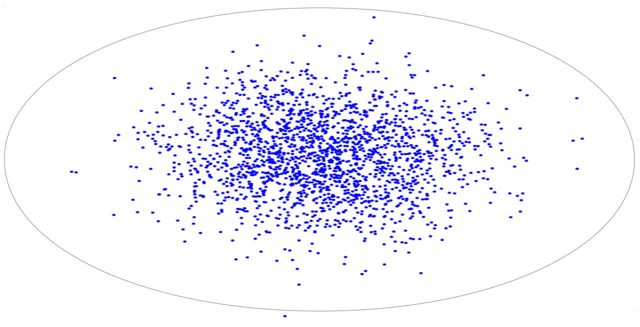
Multipole magnet errors
(imperfect dipoles and quadrupoles)



Apertures



Space Charge



Multipole magnetic fields

Magnet Test Facility measured coefficients b_k, a_k

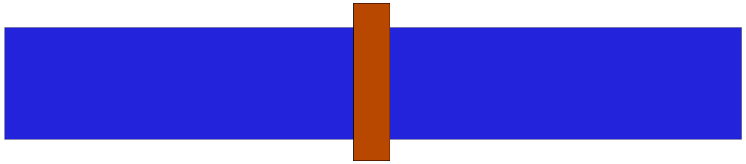
$$\text{such that } B_y + i B_x = B_0 \sum_k \frac{(b_k + i a_k)}{R_0^k} (x + i y)^k$$

k up to 6 (tetradecapole) for most dipoles and quadrupoles

R_0 is the radius of the measuring coil (1 inch)

Mean and standard deviation for most magnets compiled and summarized in tables by A. Drozhdin and B. Brown

A set of random multipoles are generated for the ring. A thin multipole element is (virtually) inserted in the middle of each dipole and quadrupole.

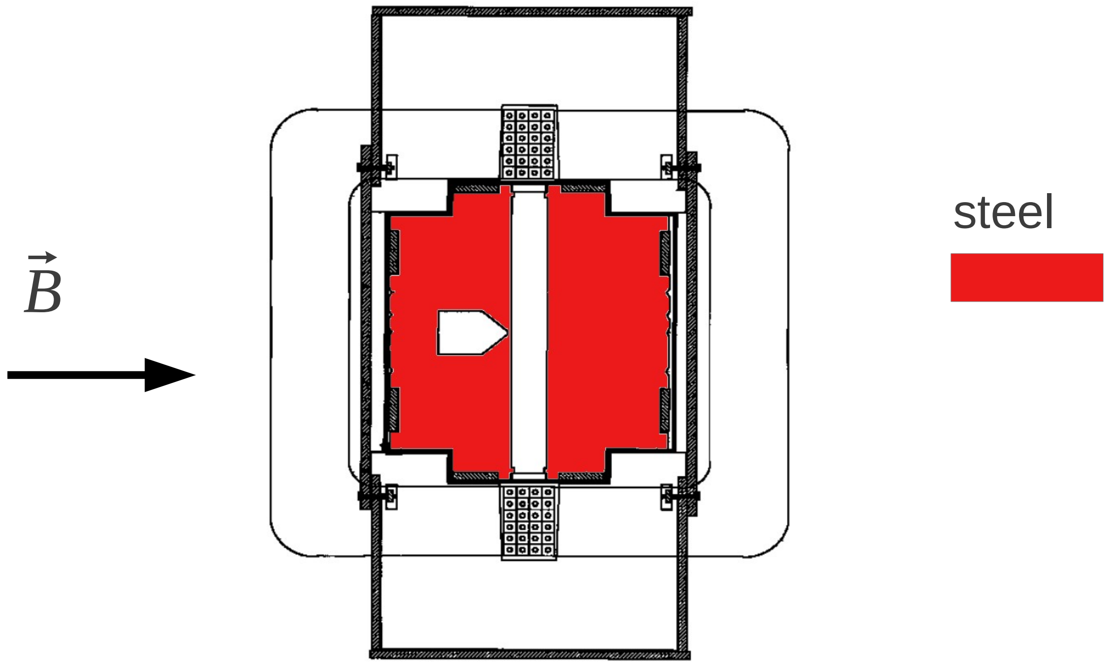


Lambertson Magnet Apertures

The main apertures of concern are the extraction lambertson magnets in the MI52 area.

There are three magnets LAM52A, LAM52B, LAM52C.

The extraction field is to the outside region of the magnet. The beam central orbit is shifted to the inside.



Getting the correct orbit

Corrector magnet settings

Name	Length [m]	Field [kG]	comments
H520	0.3048	0.231776	BCB memo
H522	0.3048	-0.013330	Fit to close orbit
H524	0.3048	0.267710	Fit to close orbit

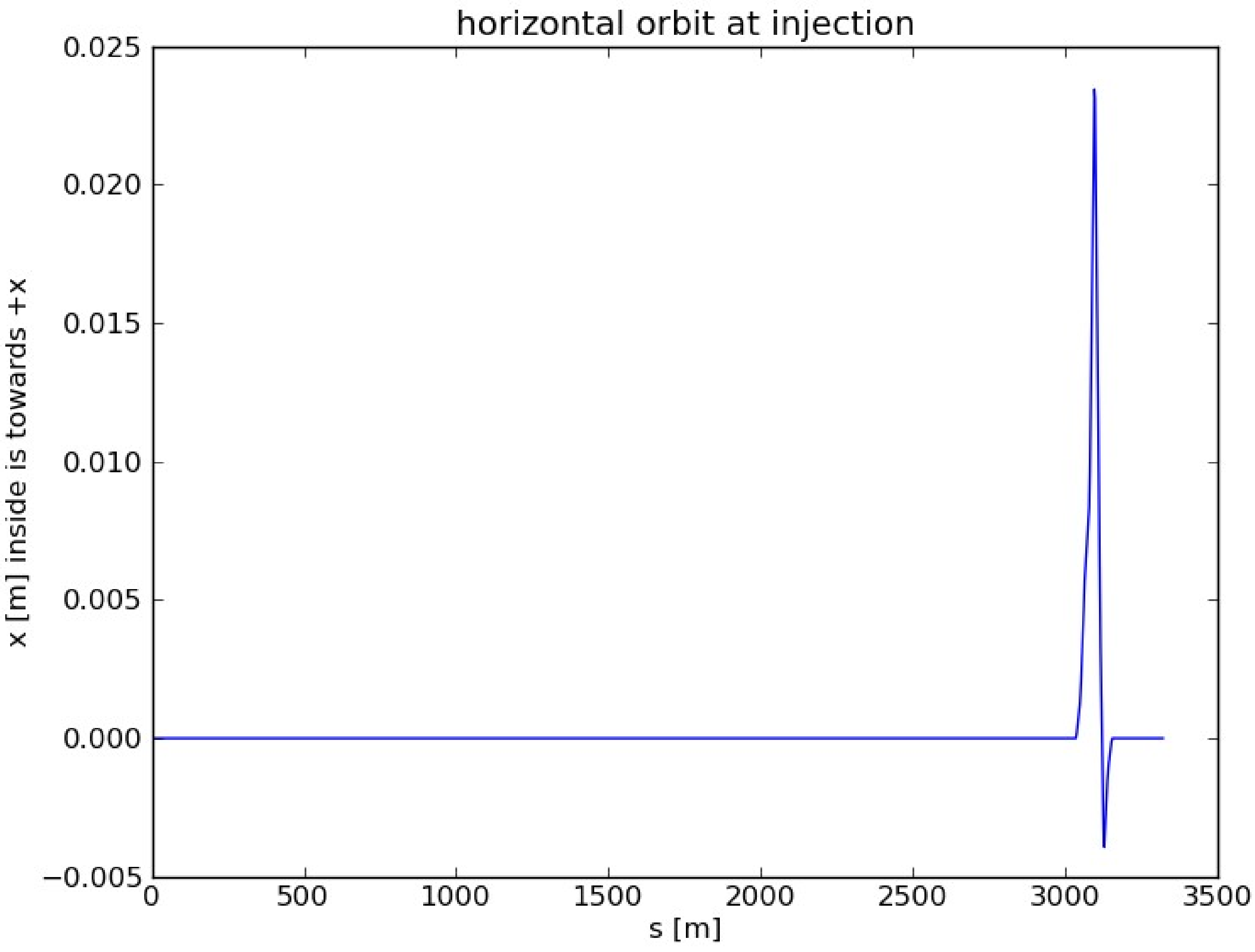
Magnet displacements

Magnet	Horizontal [mm]	Vertical [mm]	comments
IQD016	+0.951	0.0	DEJ email 2012-06-21
IQC022	+1.927	0.0	DEJ email 2012-06-21
IQE072	-0.288	0.0	DEJ email 2012-06-21
IQD024	+1.689	0.0	DEJ email 2012-06-21
IQD018	-0.822	0.0	DEJ email 2012-06-21

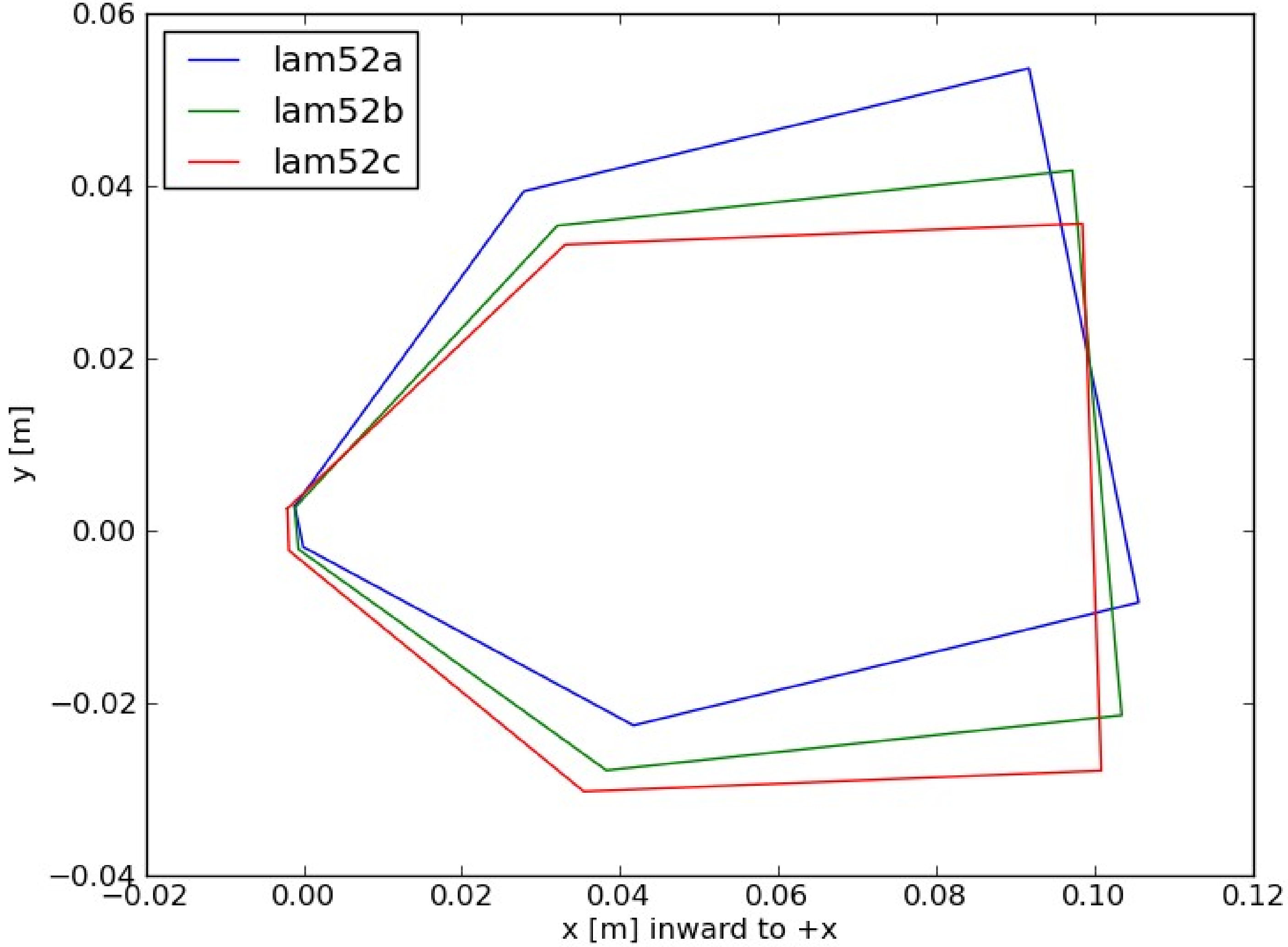
Other lambertson positions at MI62, MI22 and MI32 are related to antiproton running which is no relevant, I do not have to include them.

Orbit bumps

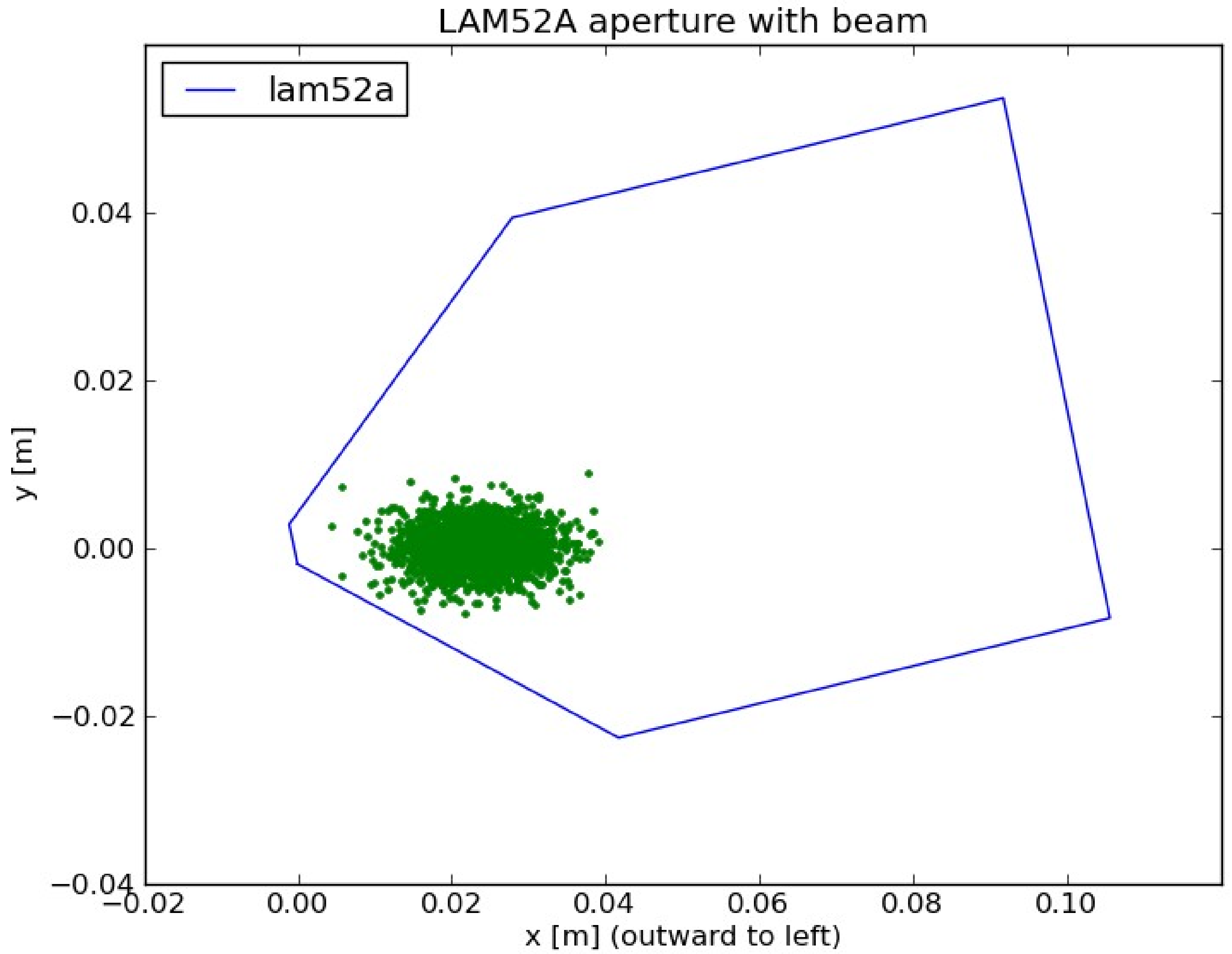
To accommodate the off-center position of the lambertson field-free region, the corrector magnets and magnet displacements shift the central orbit to the inside of the ring (+x) for counterclockwise circulating protons.



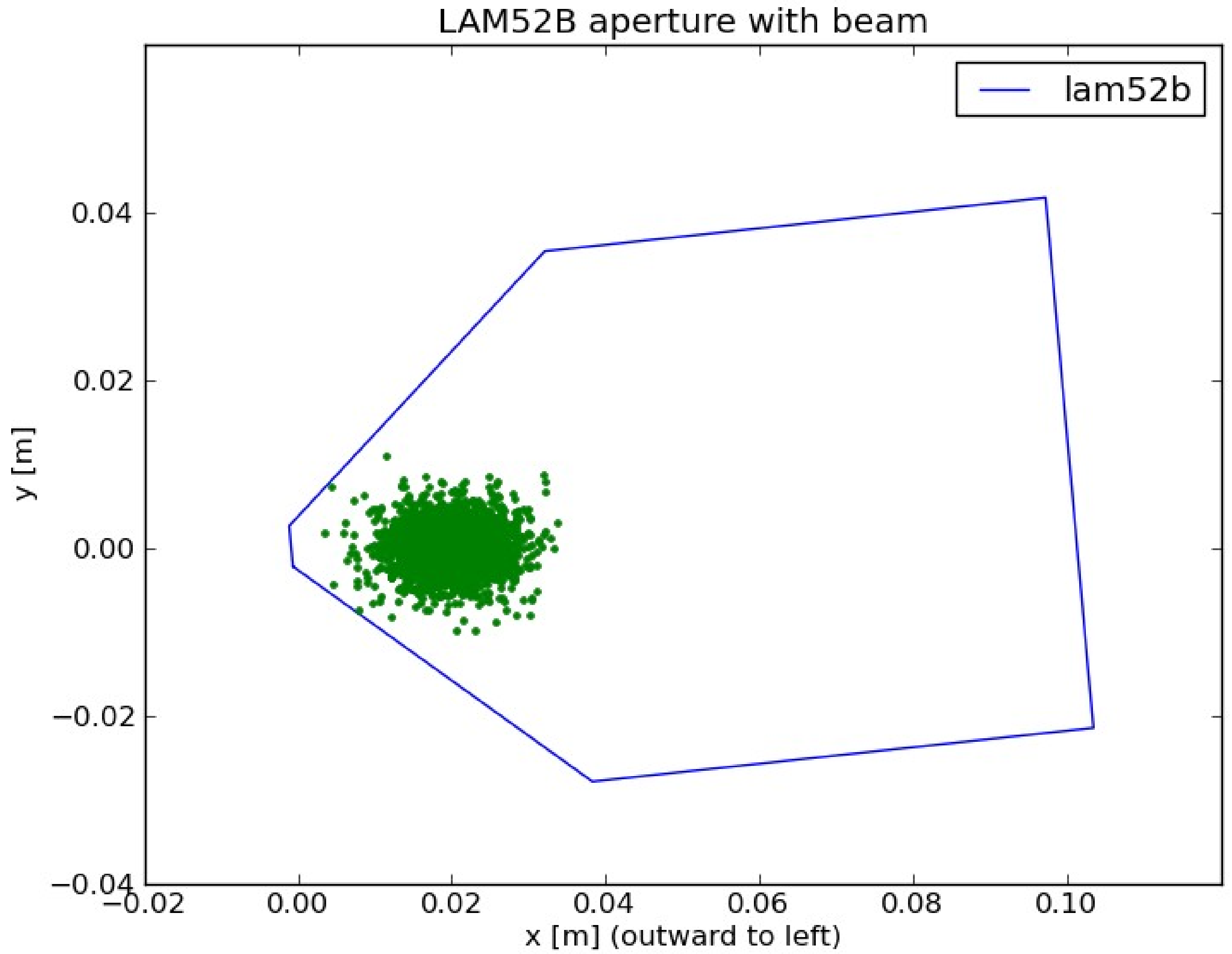
Overlay position of LAM52{A,B,C} apertures



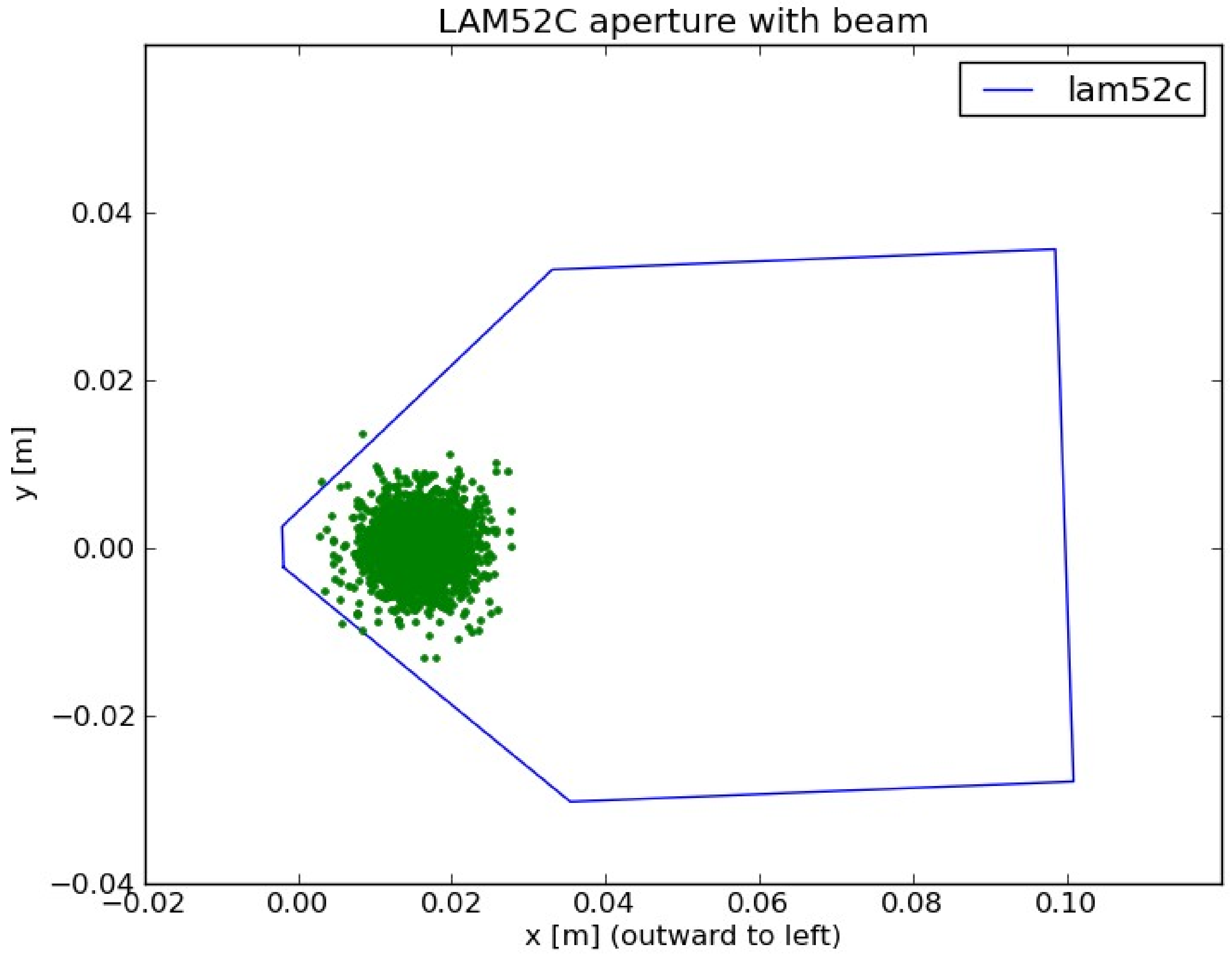
Simulated beam position in MI52 lambertson apertures



Simulated beam position in MI52 lambertson apertures (continued)

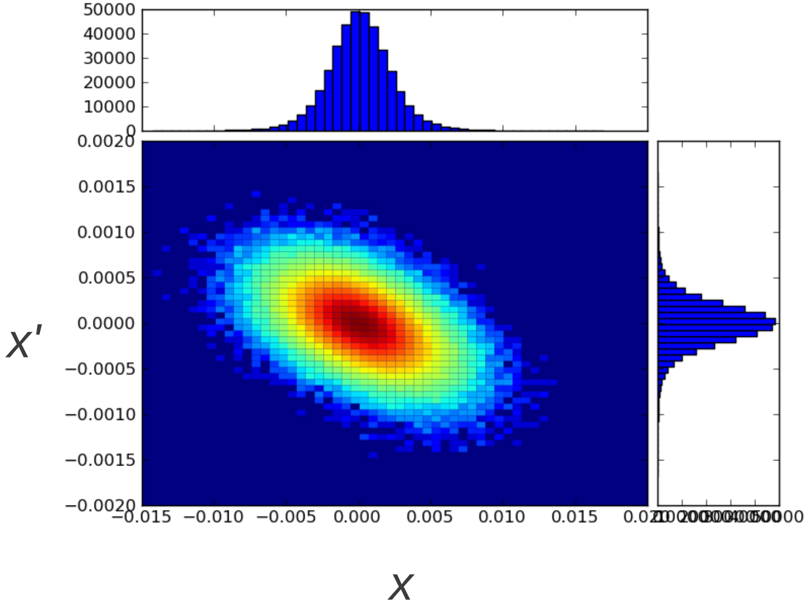


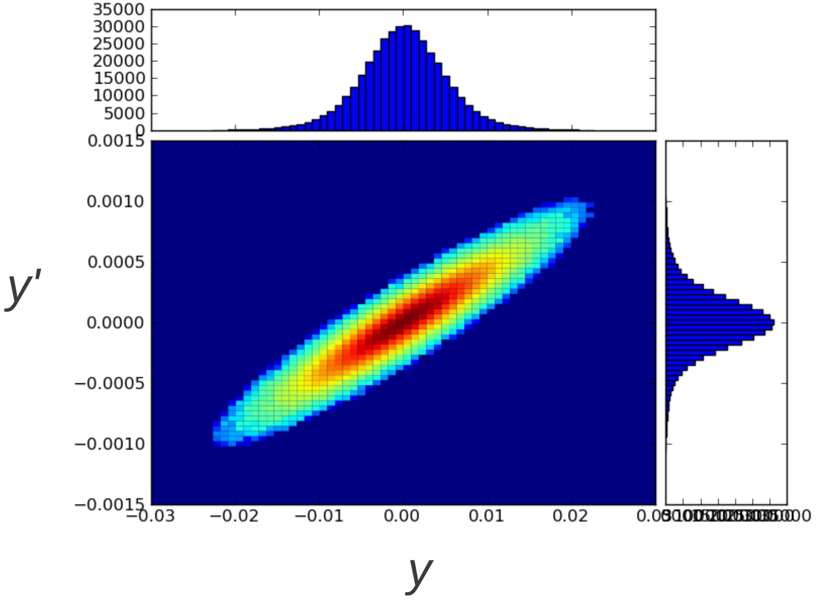
Simulated beam position in MI52 lambertson apertures (continued)



Bunch shape

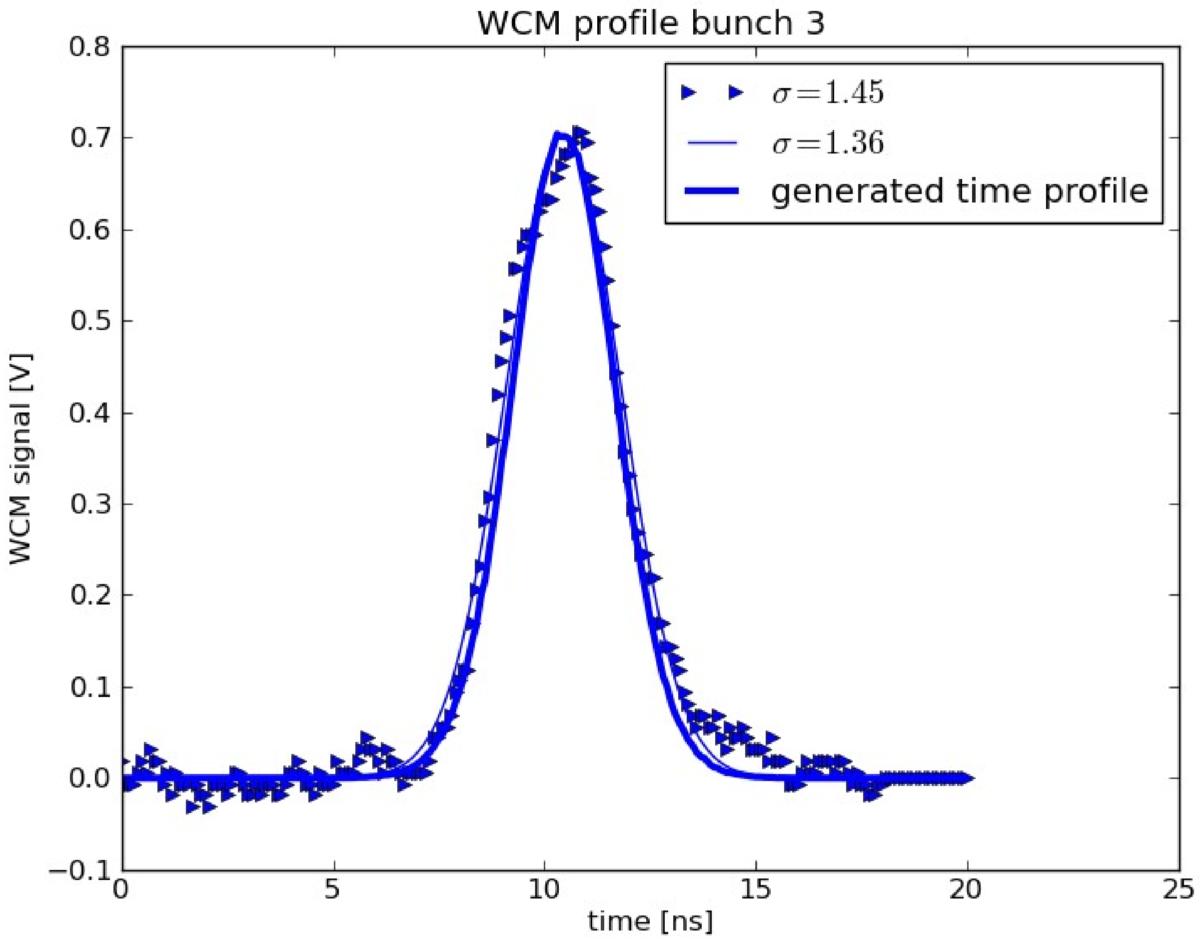
No information on transverse size, so use nominal 18 π mm-mrad emittance.   6D equilibrium beams generated with normal forms calculated with 5th order pertubation theory.





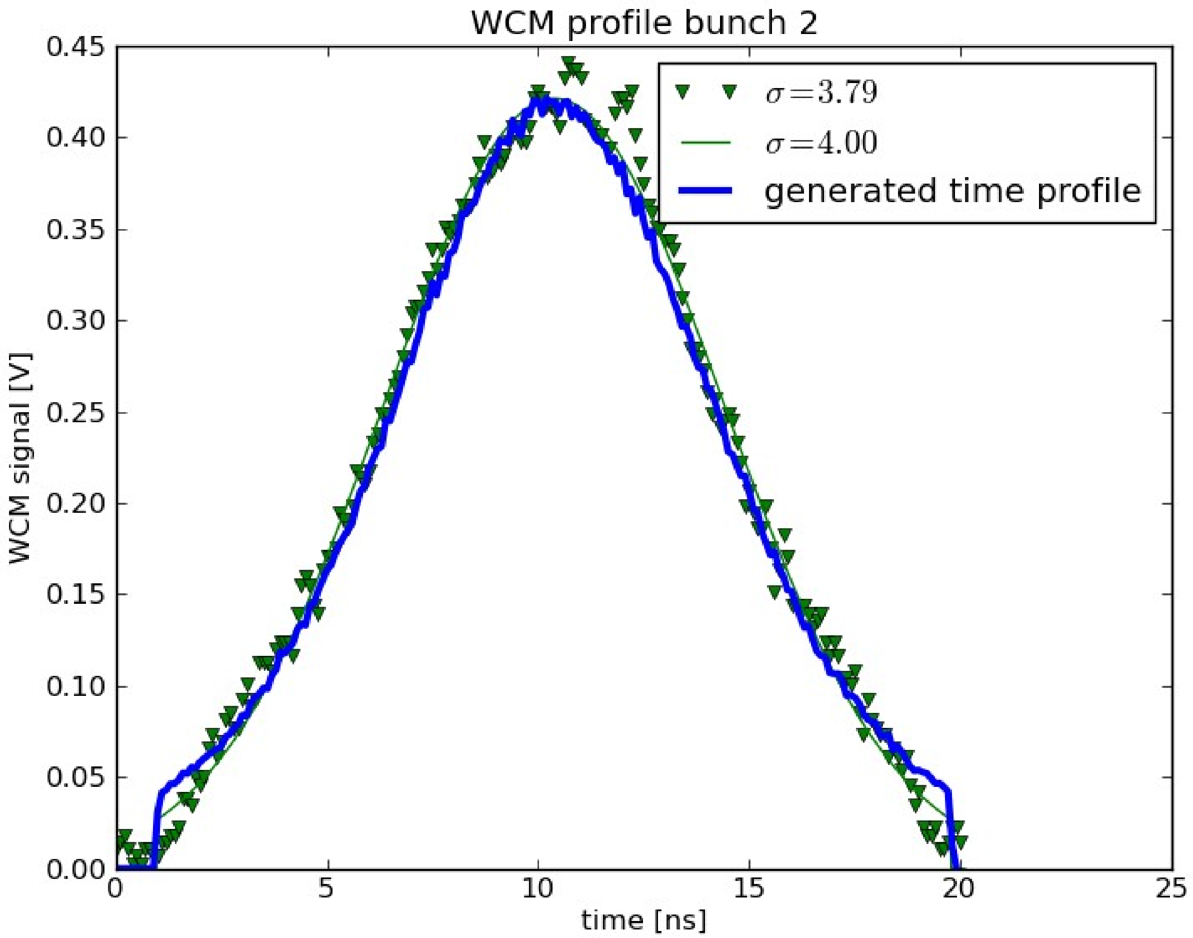
Longitudinal bunch shape (short bunch)

Short non-coalesced bunch as measured by D. Scott and as generated by Synergia.

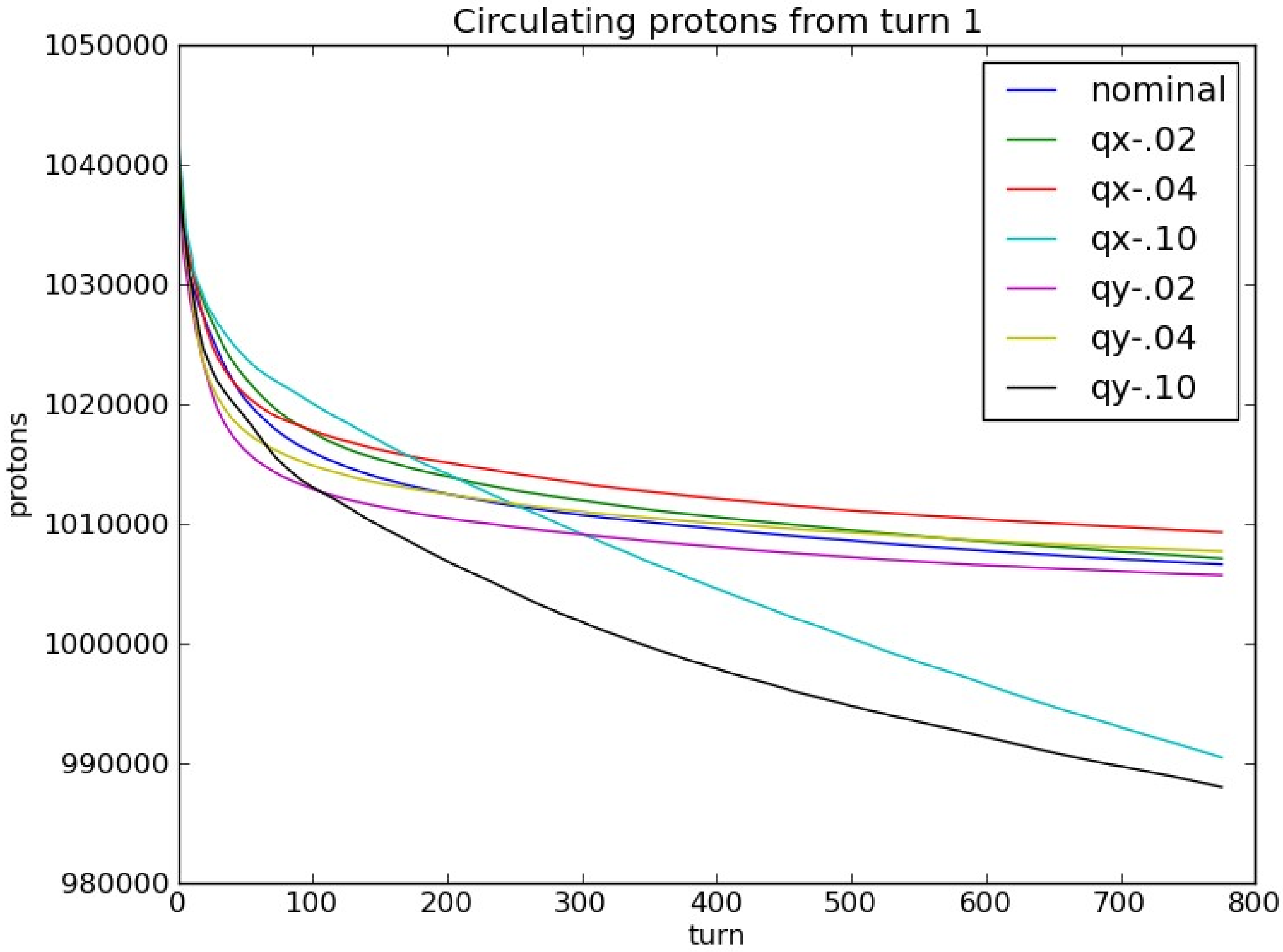


Longitudinal bunch shape (long bunch)

Longitudinal beam distribution coalesced beam measured by D. Scott and generated by Synergia. Full bucket width = 18.9 ns. Starting with a full Gaussian tails produces large initial losses. Implemented truncated Gaussian distribution with the same central shape as measured wcm profile

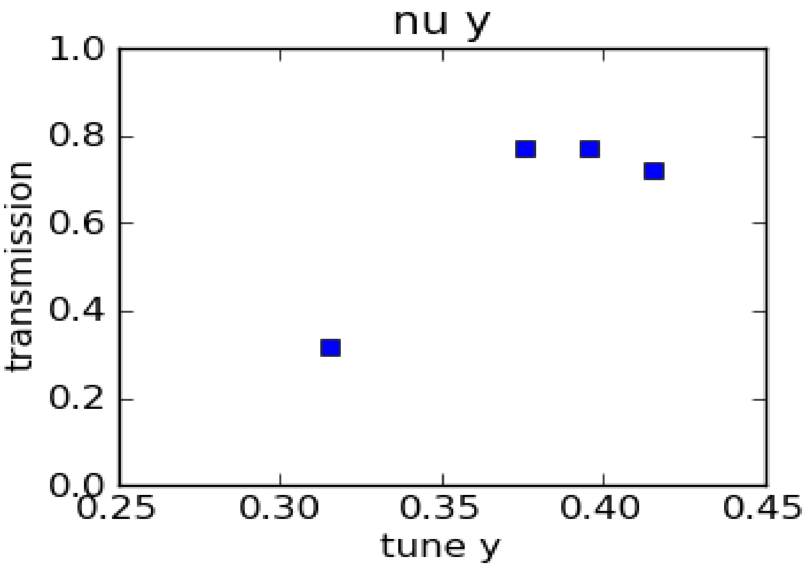


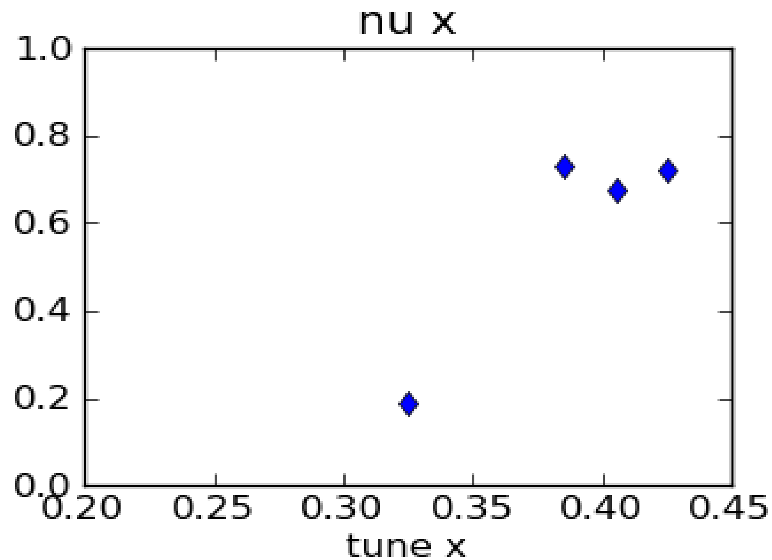
Run 775 turns with different tunes



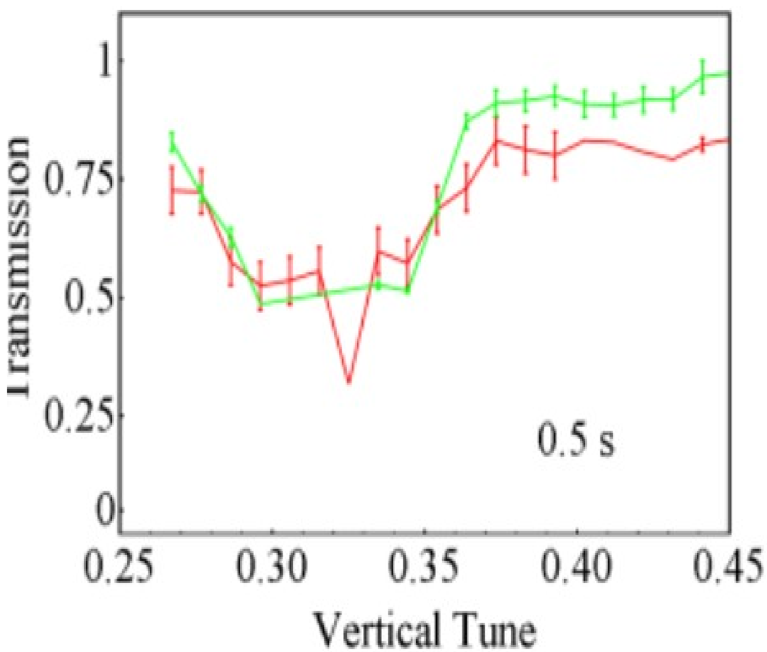
... extract transmission from exponential extrapolation of last 300 turn loss rate … (turn 775 to turn 44500)

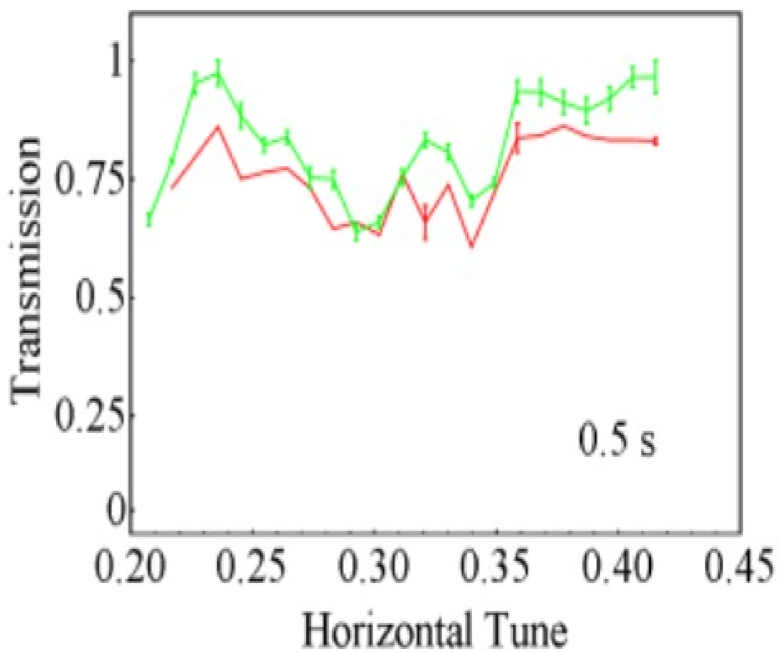
Plot transmission (0.5 s) vs tune





simulation



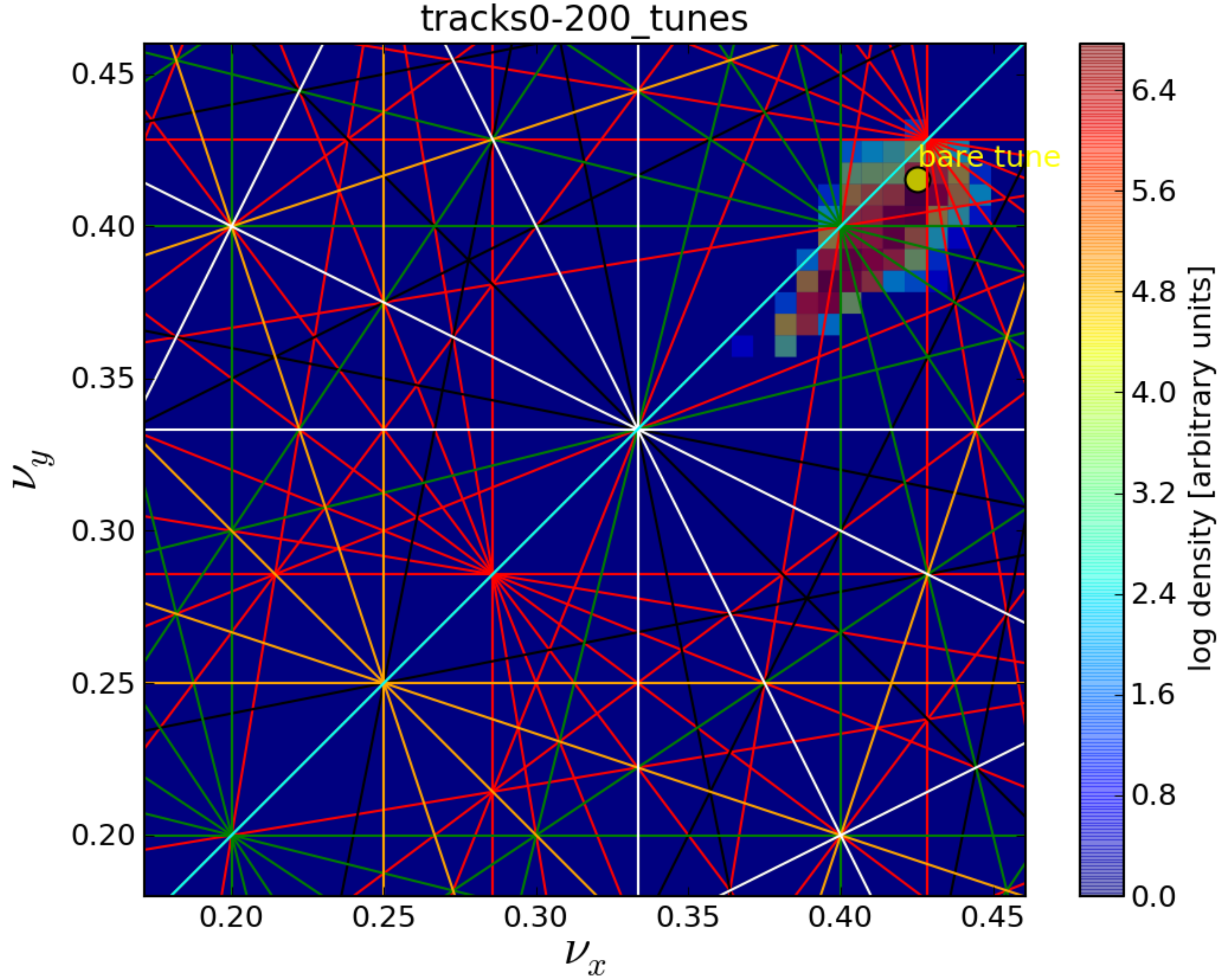


measurement

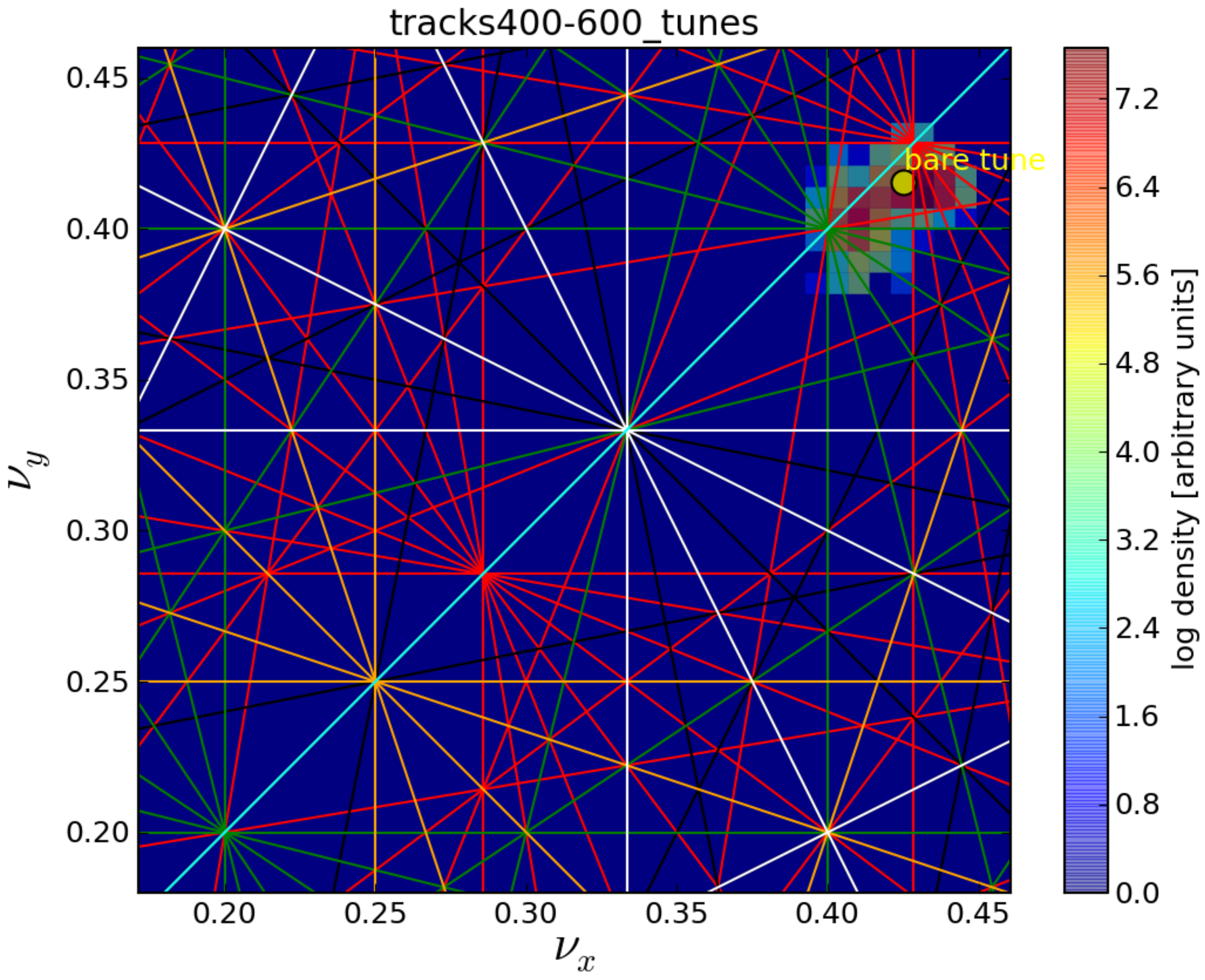
Short bunch

Long bunch

Tune footprints may tell a story: nominal tune, turns 0-200

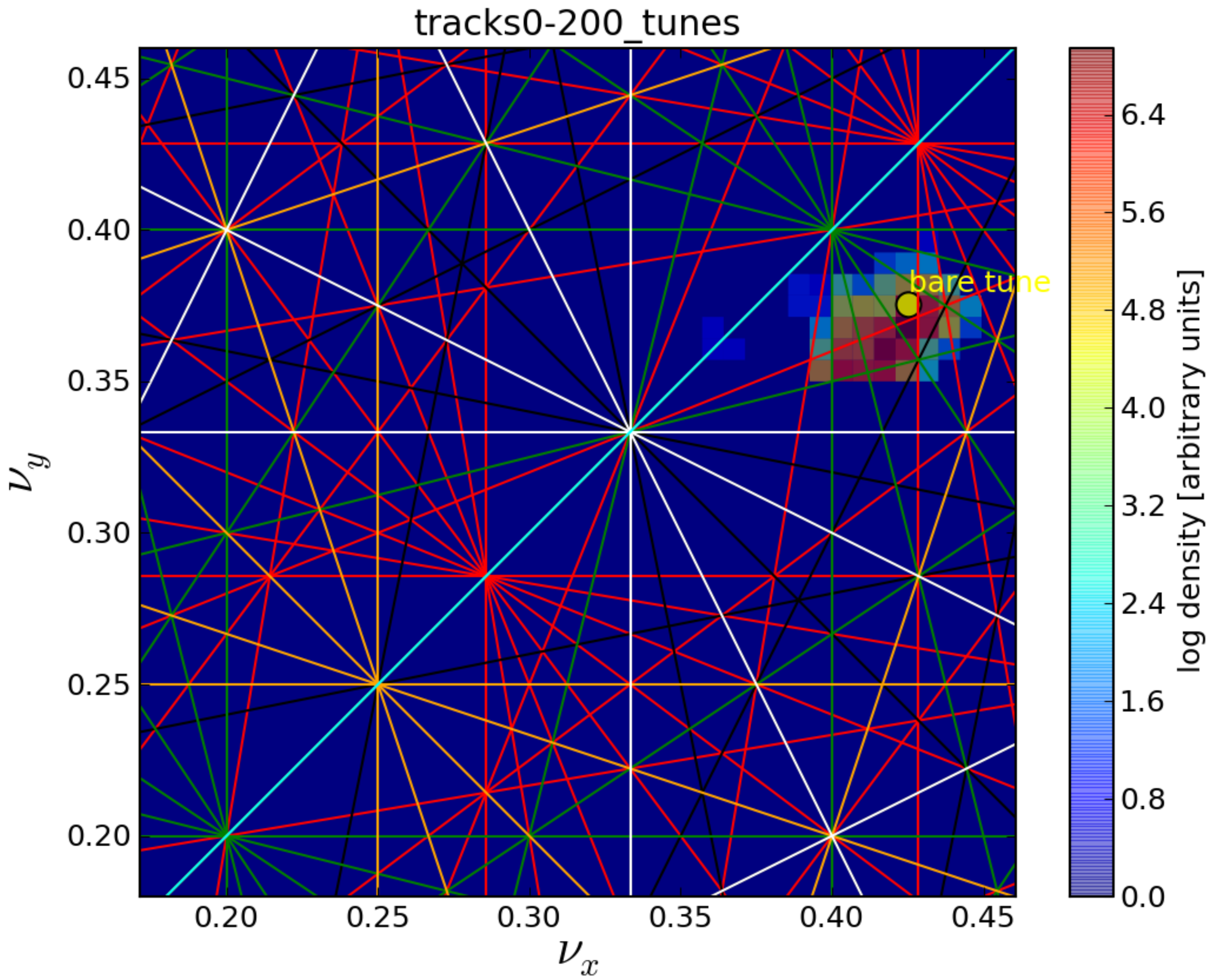


nominal tune, turns 400-600



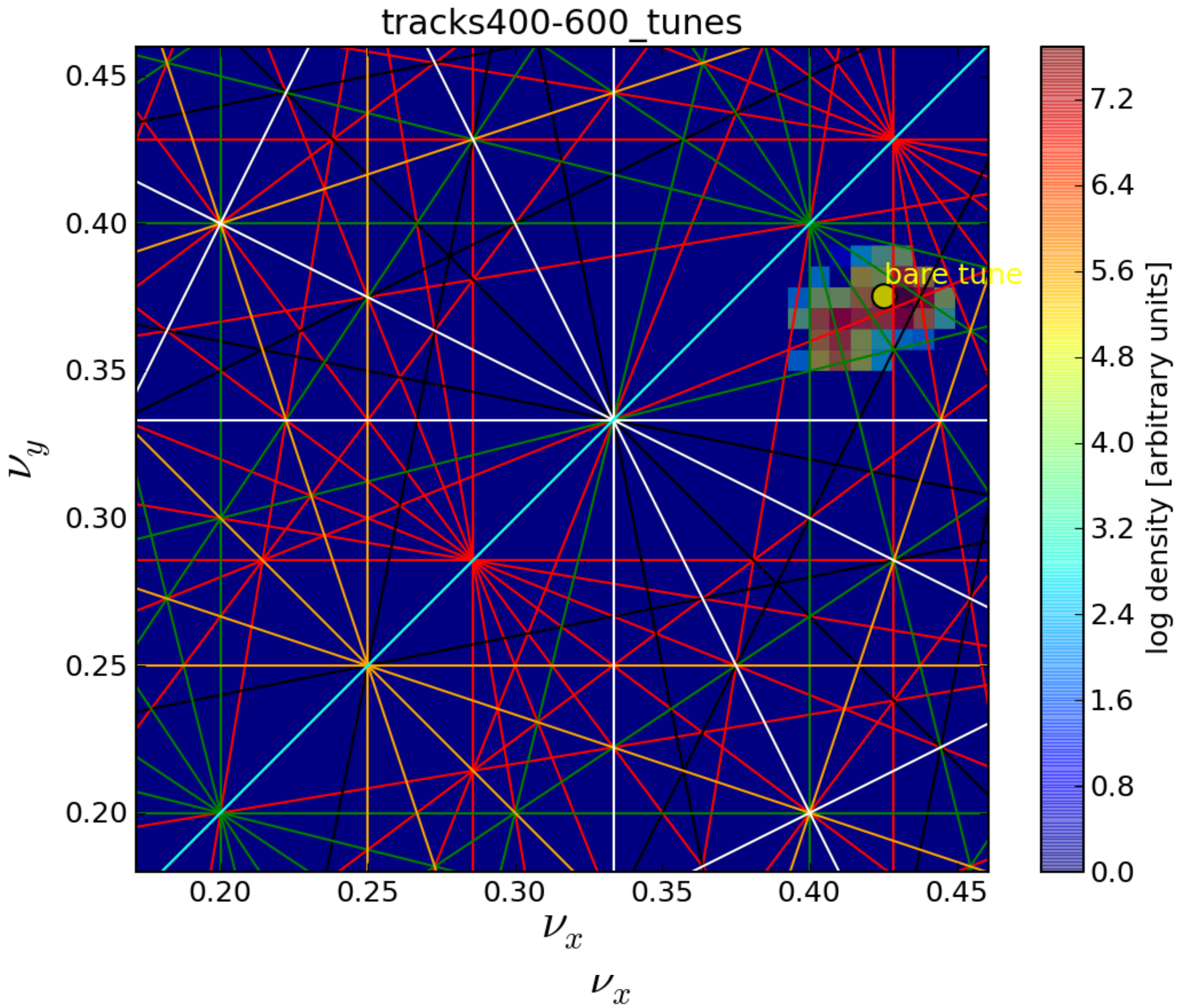
ν_x

Y tune of 0.372 has better transmission: turns 0-200



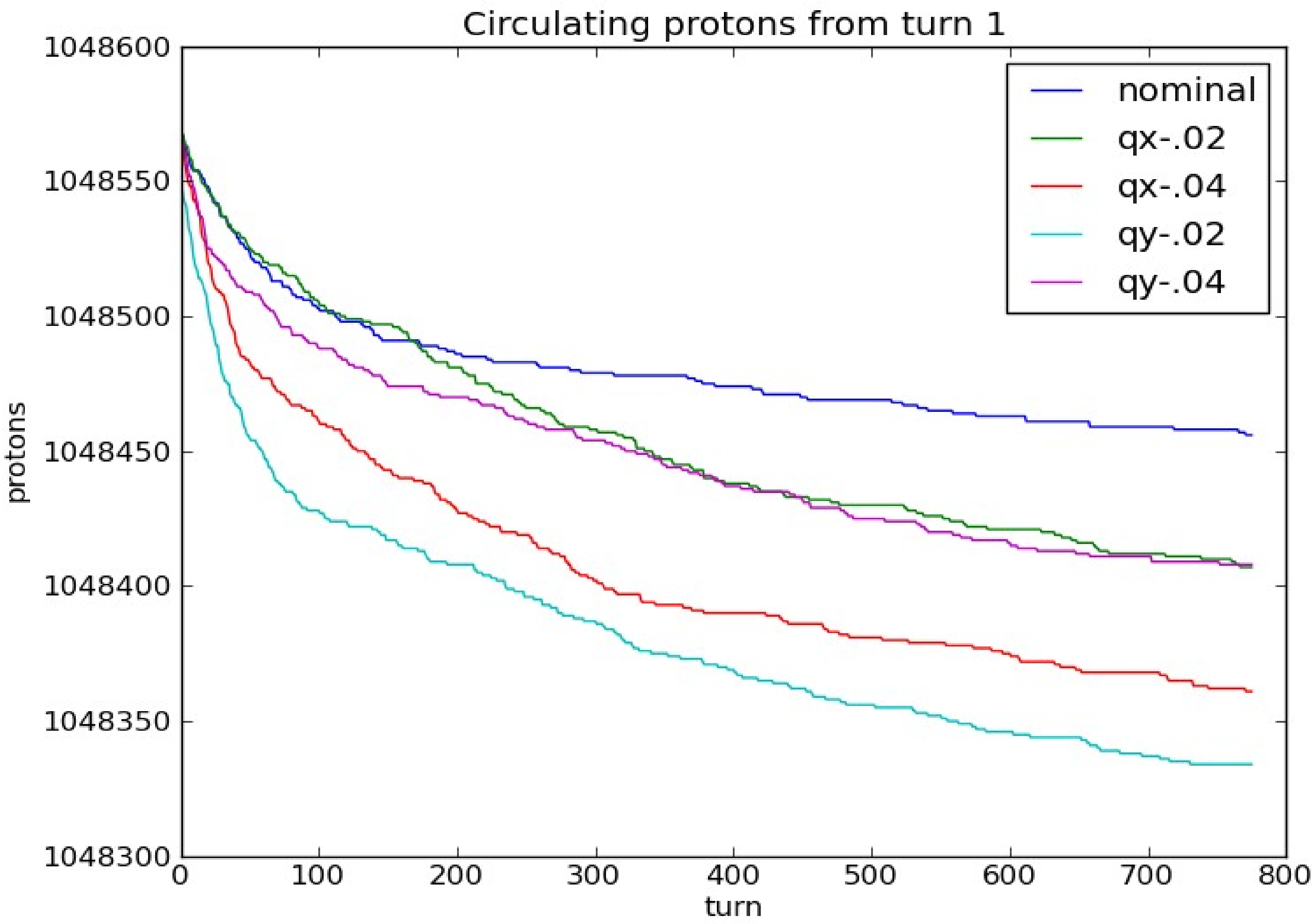
ν_x

Y tune of 0.372 has better transmission: turns 400-600



Studies with constant charge/bunch length

Charge = 3.0e10, bunch length = 0.36

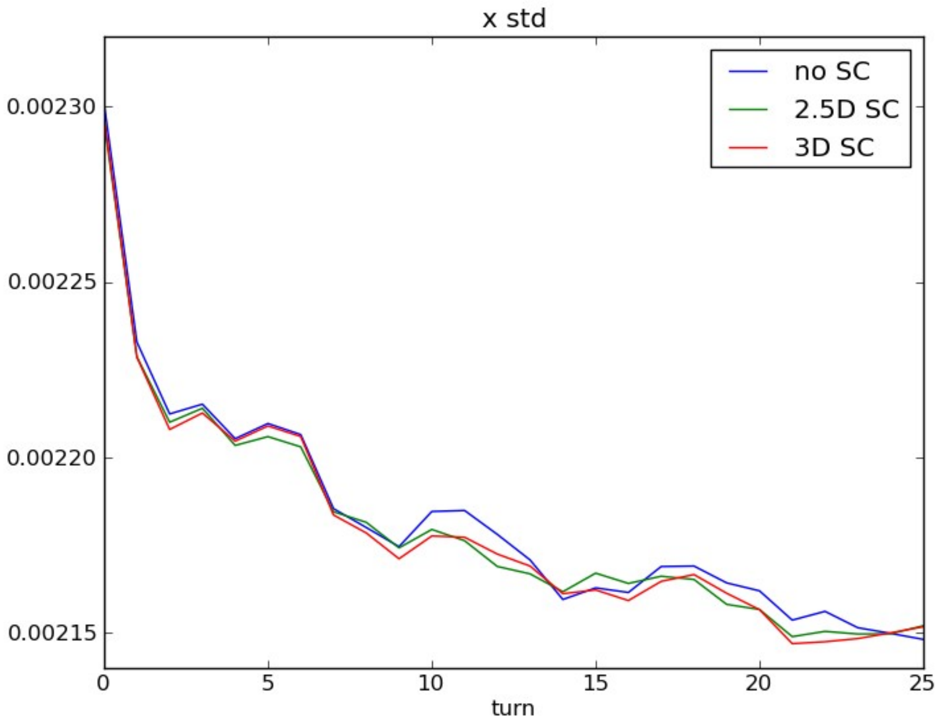


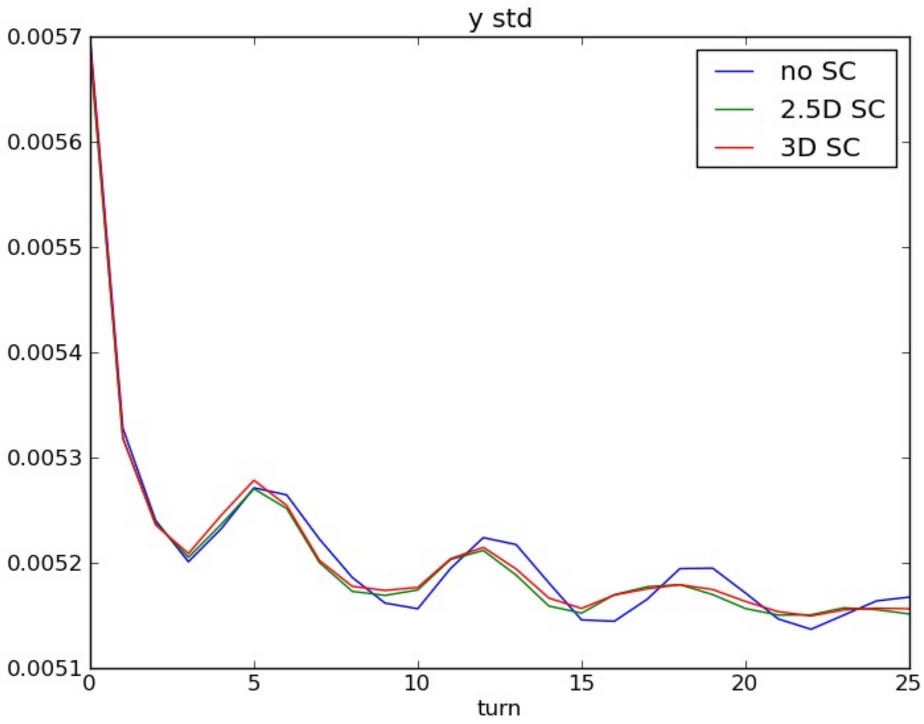
Losses are very small

I typically see losses coming from the ends of the bunch. When the bunch is short, this doesn't occur. It might happen after a large number of turns.

Optimizations

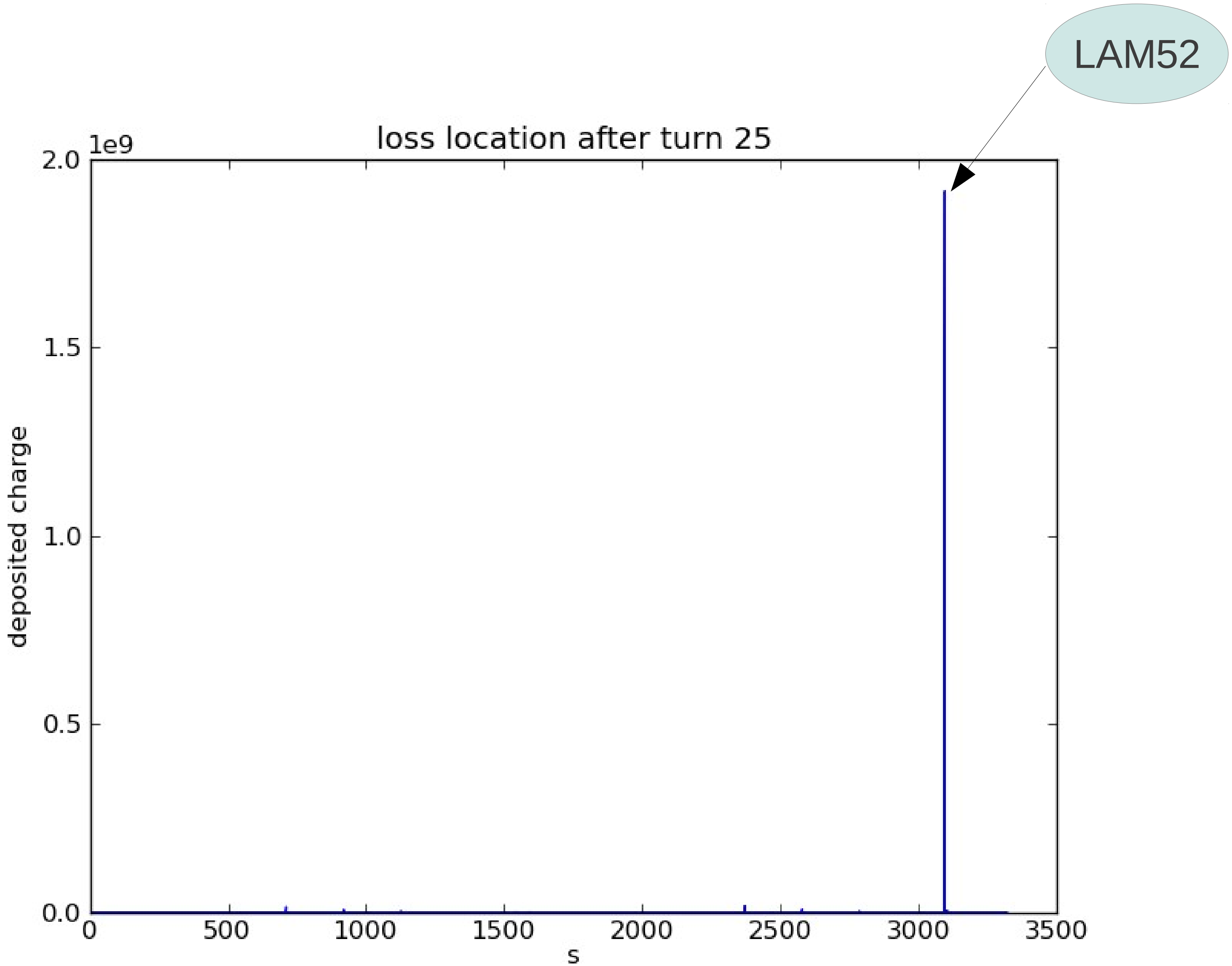
3D Space charge -> 2.5 D space charge
Multi-array initialization





Combined optimizations results in speedup from
70 s/turn to 30 s/turn

Where do losses occur?



Summary

- Machinery is in place to investigate losses in the Main Injector.
  - Simulations of long bunches are qualitatively similar to the measurements from machine studies. Longer runs are necessary to determine if there is quantitative agreement.
  - Optimizations have achieved a factor of two speedup. Recent work on Synergia optimizations for mu2e have achieved equivalent of 15K MI turns/day.
- Simulations of short bunches do not match the measurements. This probably indicates that the bunch shape is incorrect.
- I need to simulate an ensemble of different multipole sets to sample a range of possible error fields.
- Preliminary results are promising. Including more apertures and better description of the machine conditions will give even better results.